

Power Units Based on Stirling Engines: New Technologies Based on Alternative Fuels

N. G. Kirillov

OOO Innovatsionno-Issledovatel'skii Tsentr Stirling-Tekhnologii, St. Petersburg

DOI: 10.3103/S1068798X08020020

MODERN STIRLING ENGINES

Until recently, autonomous power systems based on traditional internal-combustion engines were consistent with available technology, fuel and energy reserves, and ecological conditions. However, current national problems such as resource depletion, the intensifying energy crisis, environmental pollution, and the greenhouse effect require urgent solution. As a result, national and international legislation relating to ecology, nature conservation, and energy conservation (for example, the Kyoto Protocol) went into force at the end of the twentieth century. These agreements called for reduction in CO₂ emissions, resource and energy conservation, the adoption of clean fuels, and other measures.

In view of the scale of fuel production, increase in its costs, and catastrophic environmental pollution, scientists and designers must search for new energy-conversion technologies. A new technology based on highly efficient thermodynamic cycles and also new fuels and working media is required; in other words, we need to create clean energy systems capable of meeting industrial and domestic demand, with minimum resource consumption. In the last two years, the price of traditional petroleum products in Russia has more than tripled. We are on the brink of energy and ecological crises. Therefore, it is time to envision alternative motors for stationary equipment and vehicles. In this context, in particular, Stirling engines are of interest.

In reviews of energy conversion, the Stirling engine is regarded as the most promising for further development. Thanks to its low noise, low exhaust-gas toxicity, adaptability to different fuels, long life, and satisfactory mass and size, the Stirling engine may be widely used in the near future. There is a possibility that it will largely replace the internal-combustion engine.

The Stirling engine has an external heat supply. In contrast to the internal combustion engine, the combustion in Stirling engines occurs outside the working cylinders and is more uniform. The closed working cycle is characterized by relatively slow pressure rise in the cylinders; the thermohydraulic changes of the working

gas in the internal loop are smooth, thanks to the absence of a gas-distributor valve mechanism.

The structure of the Stirling engine is shown in Fig. 1. It consists of an optimal combination of a compressor, a compressed-gas motor, and heat exchangers: a heater with a combustion chamber, a regenerator, and a cooling unit. As a rule, the working medium is helium, which undergoes a direct thermodynamic cycle in the internal loop: two isotherms and two isochores.

Stirling engines have properties that permit their use practically throughout industry and engineering, including the following:

- (i) a universal thermodynamic cycle, permitting the creation of motors of power ranging from a few W to 1 MW;
- (ii) high energy efficiency (the theoretical efficiency of the cycle of an ideal Stirling engine matches that of the Carnot cycle);
- (iii) low environmental impact of the working medium and the spent combustion products, with various fuels;
- (iv) the ability to use both traditional and nontraditional heat sources (solar energy, natural gas, peat, coal, etc.).

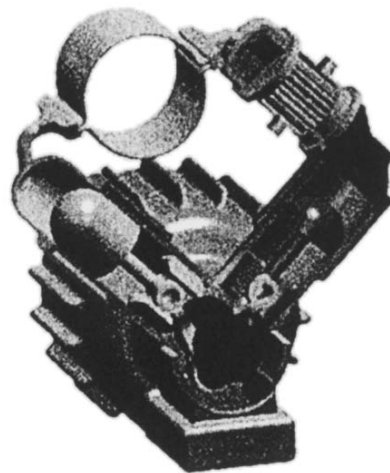


Fig. 1.

Table 1

Manufacturer	Motor	Power, kW	Mass/power ratio, kg/kW	Working life, h	Efficiency, %
Philips	4 × 235	150	5.0	10000	28
	4-S-1210	265	3.8	10000	30
STM Inc.	STM4-20	52	2.1	50000	45
	SM-3	40	–	50000	40
Daimler Benz	KS15D	15	3.7	–	37.1
Solo	V-160	7.5	2.3	28000	35
MTI	Mod III	108	3.0	20000	36
	4-95	52	4.1	20000	41
United Stirling	V4X	1250	1.2	10000	30

Engineers in many countries are at work on the development of Stirling engines, which are characterized by low environmental impact, low noise, the absence of gas-distribution and ignition systems, and high fuel economy. Several firms are mass-producing Stirling engines that outperform internal combustion engines and gas-turbine engines, with an efficiency of 40% even at 600–700°C. In the best designs, the mass/power ratio is 1.2–3 kg/kW, while the efficiency is 45%. Table 1 presents the characteristics of some foreign Stirling engines.

Power units equipped with Stirling engines are very clean and practically noise-free; the concentration of harmful components in the combustion products is an order of magnitude less than in diesel engines. Table 2 compares the toxicity of spent gases for various systems.

The efficiency of power units based on Stirling engines may be attributed to their compactness, mass, and fuel economy. Installing Stirling generators in the immediate vicinity of the demand reduces transmission losses.

COGENERATION SYSTEMS WITH NATURAL-GAS STERLING MOTORS

Stirling engines are promising for use in cogeneration units of power up to 100 kW, generating electric power and heat at the point of demand (for example, in residential and public buildings). This is especially important where dilapidation of centralized power systems and heat-supply networks results in enormous heat losses and interruptions of power supply.

Cogeneration systems may be based on autonomous motors and heat-recuperation systems, in which the energy of the coolant liquid and the spent gases is used for heating purposes. Stirling engines are more efficient

than internal combustion engines in cogeneration systems on account of their thermal balance, i.e., the difference between the heat extracted by the spent gases and the heat extracted by the coolant liquid. For Stirling engines, this difference is 30%. Taking account of their high efficiency, this permits the creation of compact and highly efficient cogeneration units.

The efficiency of modern Stirling generators is more than 40%. On heating the working medium to 90°C, the total efficiency is 95%. In Germany, the United States, New Zealand, Australia, and elsewhere, cogeneration systems with Stirling engines of electrical power 5–40 kW and thermal power 12–120 kW are in production.

A 9.5-kW natural-gas Stirling engine is shown in Fig. 2. This motor is part of a cogeneration system generating around 30 kW of thermal energy.

Table 2

Power unit	Content of harmful components in spent gases, g/kW h		
	CO	CH _x	NO _x
Motor with forced ignition, gasoline fuel (Otto carburetor)	38.1	2.72	21.8
Motor with forced ignition, fueled by burned natural gas	35.4	4.10	17.7
Diesel engine with direct fuel injection	4.9	3.0	11.7
Diesel engine with prechamber mixing	2.3	0.27	7.9
Vapor engine	5.7	0.34	4.1
Open gas turbine	6.0	1.22	2.72
Stirling engine	3.8	0.20	2.45

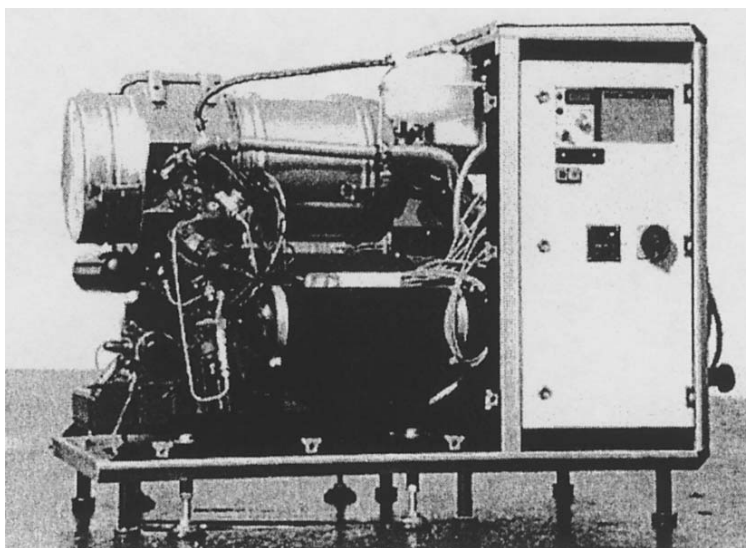


Fig. 2.

Cogeneration systems based on natural-gas Stirling engines permit 40% reduction in fuel consumption relative to centralized power systems. The cost of 1 kWh of power from a cogeneration system is 3–4 times less than for centralized power systems, and the heat generated is essentially free! Cogeneration units provide an effective supplement to heat- and power-supply systems, with no need for reconstruction of the overloaded old systems. The autonomous operation of a cogeneration unit provides consumers with heat and electric power and helps to stabilize their parameters.

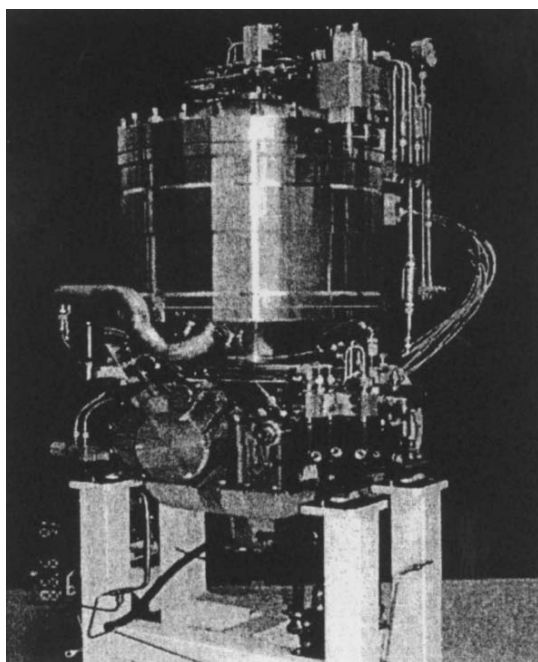


Fig. 3.

STERLING ENGINES BASED ON NATURAL GAS AND BYPRODUCT GASES

Autonomous power units with Stirling engines (Stirling generators) are irreplaceable in the oil and gas industry, on introducing new fields, especially in the Far North and on the Arctic Shelf; power is required here for prospecting, drilling, welding, and other uses.

In these conditions, possible fuels are unpurified natural gas, byproduct gas extracted together with the oil, and gas condensate. Thanks to the wide range of possible fuels, Stirling generators are universal energy sources. Thus, supplying energy to drilling units, observation stations, communications systems, and other autonomous systems is not a problem.

According to preliminary calculations, a 100-kW Stirling generator operating on natural gas or byproduct gas may supply power and heat to observation stations housing up to 50 gas and oil specialists or geologists. There is no need to deliver fuel from the mainland. Environmental impact is reduced on account of the minimal spent-gas emissions. A 75-kW Stirling engine is shown in Fig. 3.

Currently, up to 15 billion m³/yr of byproduct gas is produced in Russian oil fields. It is difficult and expensive to collect and cannot be used as fuel in internal-combustion engines on account of its fluctuating fractional composition. Therefore, to prevent environmental pollution by this gas, it is burned off. However, this gas may be used as fuel in Stirling-motor power units.

Power units with (3–8)-kW Stirling engines are expedient for automation, communications, and cathode-protection systems at gas pipelines, while more powerful systems (from 100 kW to 1 MW) are irreplaceable for marine and land drilling systems in the oil and gas industry.

STERLING ENGINES RUNNING ON GENERATOR GAS

Currently, given the exhaustion of organic-fuel reserves and the rising prices of oil and natural gas, the mass production of (3–500)-kW power generators with modification of the Stirling engine for local fuel is of considerable interest in Russia. Possible fuels include peat, ground coal, shale, agricultural wastes, and wood chips. In the near future, such Stirling generators will provide many regions of Russia with inexpensive autonomous power sources.

The use of biofuels is not a return to the past, but a reasonable economic and ecological approach. We know that the Russian sawmills waste 50% of the incoming timber, to which may be added the comparable waste in woodworking and furniture making. Agriculture generates considerable quantities of biomass each year.

The use of autonomous power sources based on local fuel is a global trend. It is most advanced in countries with considerable bioresources (wood, peat bogs, etc.), such as Sweden, Norway, Denmark, Finland, and the Baltic nations. Sweden has made great strides in using local biofuels: natural gas accounts for no more than 2% of power generation, as against 21% for bioresources. Biofuels represent 12% of power generation in Austria and 23% in Finland. Overall, around 14% of total energy generation in the Economic Community may be attributed to bioresources. In India, the decentralization program for power generation initiated in 1995 calls for the satisfaction of 44% of demand on the basis of bioresources in the near future.

Many regions in Russia have enormous reserves of inexpensive local fuel. For example, Karelia has considerable reserves of renewable biomass in the form of woody plants, peat, and agricultural wastes, which may be used as a fuel. Peat reserves in Karelia amount to 2 billion tn; reserves of wood from deciduous forests amount to around 2 million m³/yr. The use of peat and wood alone may reduce fuel imports by 60%; this is practically a third of Karelia's budget.

The use of autonomous power systems based on Stirling engines would permit rapid introduction of generators consuming local fuel in the northwestern, central, and Siberian regions of Russia. Outside Russia, (5–50)-kW Stirling engines fueled by wood chips are already in production. A power unit with a Stirling engine is shown in Fig. 4; its operating system and energy balance are illustrated in Fig. 5. This unit is intended for the cogeneration of electrical energy (30 kW) and thermal energy (100 kW). Wood-processing wastes serve as the fuel.

Stirling generators may also be used for the gasification of biomass. Gasification of waste wood yields a fuel gas that contains CO, H₂, and N₂. It may be used as a gaseous fuel for Stirling engines. The calorific value of the generator gas produced is 12–13 MJ/kg; its den-

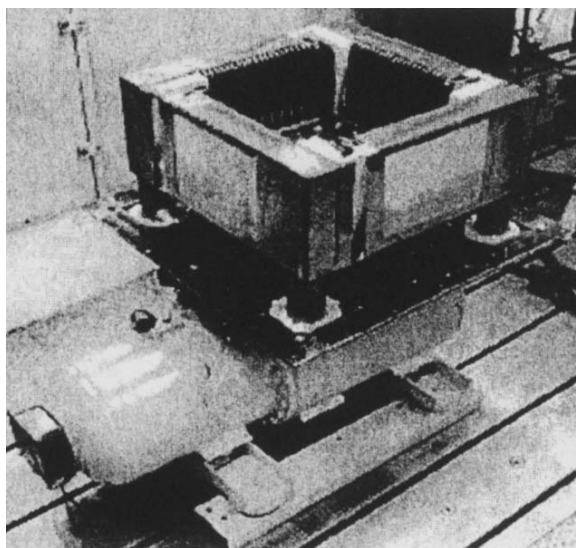


Fig. 4.

sity is 1.10–1.15 kg/m³. The gas yield is 1.8–2.5 m³/kg of biomass. Thanks to the efficiency of gasification (the yield of generator gas is 85–90%) and its convenience as a fuel, this method is cleaner and more efficient than solid-fuel consumption in a boiler furnace. An important benefit is that low-quality fuel (shavings, dust, ground-up bark) may be used in the generator.

A 50-kW Stirling engine based on generator-gas fuel is shown in Fig. 6.

Gas generation from waste wood is a source of inexpensive thermal energy. A gas generator combined with a Stirling generator may provide heat and power for any remote population center. Wastes such as bark and branches may serve as fuel. Low-quality wood waste, of low efficiency and high moisture content (up to 50%), may be burned in the generator. Pieces as large as 30 cm may be used.

The gas generator converts solid fuel to gaseous fuel at high temperature, in the absence of oxygen. This process is known as pyrolysis. The result is wood-based generator gas of calorific value no less than 1100 kcal/m³. The gas generator is of simple design and does not require highly qualified operating staff. The generator consists of three components: gas-generating chambers, ignition chambers, and a charging bunker. Thermally stable material is used for the generator, since it operates at high temperature.

OOO Innovatsionno-Issledovatel'skii Tsentr (IITs) Stirling-Tekhnologii is currently developing a standardized design for a power system serving up to 50 houses in a small community, on the basis of Stirling cogenerators with generator-gas fuel.

Stirling generators combined with gas generators are highly practical, on account of the production of inexpensive thermal and electrical energy, the use of

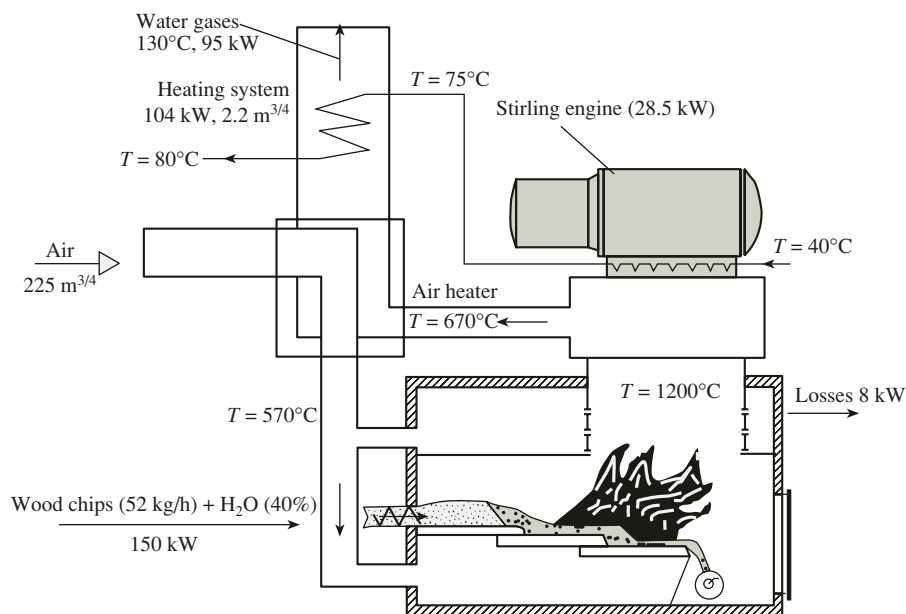


Fig. 5.

local fuel, their location at the point of demand, the absence of expensive transmission lines and substations, their low environmental impact, and their mobility.

ANAEROBIC POWER UNITS WITH STERLING ENGINES BASED ON BURNED NATURAL GAS

Anaerobic (air-free) autonomous power systems do not use air. Such systems include sources of high-temperature heat, direct-cycle energy converters, and auxiliary equipment.

Anaerobic systems based on Stirling engines are now in production in many developed nations, including Germany, France, Sweden, Japan, and the United States.

Between 1996 and 1998, the Gotland, Uppland, and Halland submarines with Stirling engines went into operation in Sweden. In 1998, there were successful tests of the French Saga-1 and Saga-2 submarines, with an anaerobic system based on a 200-kW Stirling engine. Mitsubishi (Japan) is testing a Stirling engine (of power more than 600 kW) developed for the new Harusio submarine. MAN (Germany) is developing a 700-kW Stirling engine for the same purpose. We know that the Viking submarine being created collaboratively by Sweden, Denmark, Norway, and Belgium will also be equipped with a high-power Stirling engine.

The explanation for the use of anaerobic power units based on Stirling engines in submarines is simple. In the view of leading specialists, such submarines already match, and in some respects exceed, the performance of nuclear submarines. Thus, in exercises in the

Atlantic, in 2003, the Halland submarine (produced by Kockums, Sweden) with anaerobic Stirling engines outperformed a Spanish submarine with an ordinary diesel-electric power unit and a French nuclear submarine. In the Mediterranean, it won a victory over the Houston nuclear submarine (USA). The efficient, low-noise Halland submarine is 4.5 times cheaper than its nuclear rivals, which may cost up to \$2.5 billion, as against around \$400 million for a diesel submarine with an anaerobic unit based on a Stirling engine.

In view of these findings, specialists from OOO IITs Stirling-Tekhnologii are developing a design for an anaerobic power unit based on burned natural gas for nonnuclear submarines (Fig. 7).

More than 40 designs for anaerobic power units based on Stirling engines have been patented, for use in submarines, special fortified buildings, and orbital space stations.

The distinguishing feature of anaerobic power units based on Stirling engines is the use of burned natural gas as a fuel. This makes use of the combustion products of hydrocarbon fuel. In addition, the submarines will be less traceable. Also, the coolant temperature in the motor's cooling system will be less than the ambient (water) temperature, thereby increasing the efficiency of the motor.

ECONOMIC EFFICIENCY OF POWER UNITS BASED ON STERLING ENGINES

The economic performance of any power unit depends on its manufacturing and operating costs. The following components may be distinguished: the devel-

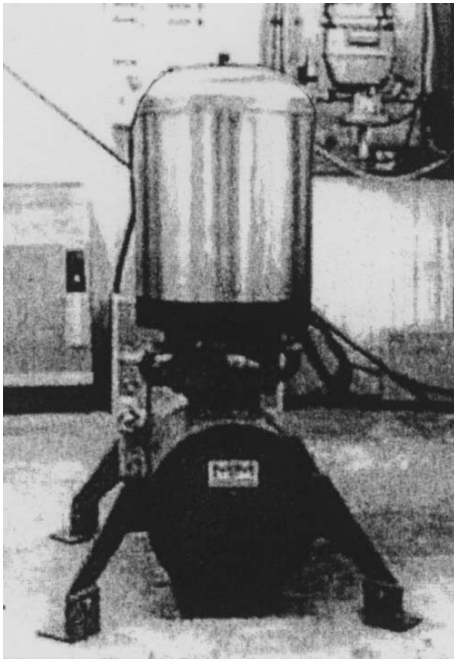


Fig. 6.

opment costs, the capital costs of the equipment, production costs, the cost of the material, operating costs, and maintenance costs. Many costs will be different for mass production or one-off production. Small-scale

production of Stirling engines shows that the cost of a single low-power motor in the production of 1000 units may be 30 times less than in one-off production.

According to estimates by Russian specialists, the following costs may be expected in small-scale production of Stirling engines in the near future: around \$12000–15000 for 10-kW motors; and up to \$80000 for 100-kW motors.

It has been established that the Stirling engine is characterized by higher manufacturing costs in small-scale production but by low operating costs, so that the initial expenditure will be quickly earned back.

PRODUCTION OF RUSSIAN STERLING ENGINES

Currently, OOO IITs Stirling-Tekhnologii has the scientific and technological basis for the creation of efficient Stirling engines in Russia. Research focuses on the use of Stirling engines in cogeneration units and systems utilizing spent-gas heat (for example, miniature heat and power plants). On the basis of years of research, a method of developing Stirling engines has been developed, and prototype motors of power 1.5–3 kW have been produced. Experiments with the prototypes confirm the possibility of creating efficient Russian motors.

In 2006, a preliminary agreement was reached between OOO IITs Stirling-Tekhnologii and OAO

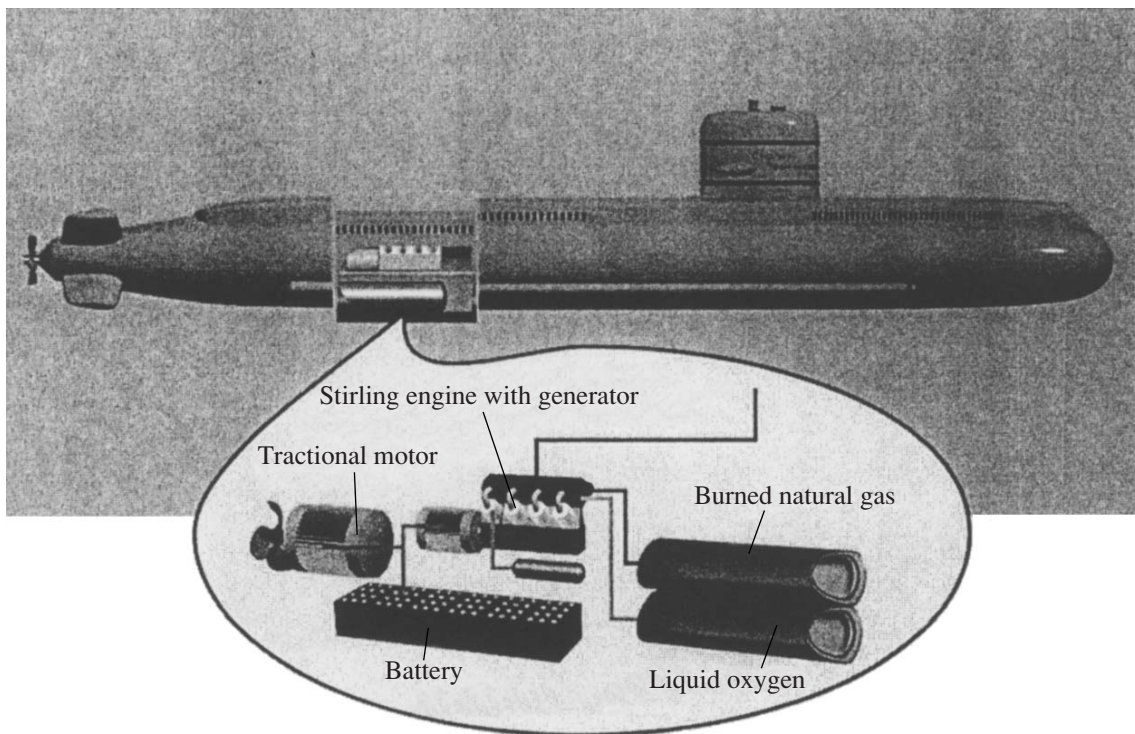


Fig. 7.

ZiD (Kovrov) for the mass production of Stirling engines in Russia. Market analysis and economic analysis of mass production are currently underway. At first, the motors will probably be produced under license from foreign companies, within the framework of dealership agreements. However, without state support, the production of Stirling engines in Russia will not be possible. In Russia, innovation, which is a very complex and risky undertaking, should be supported by the state, especially at startup, with subsequent transition to a purely commercial basis. In creating the large-scale production of Stirling engines in Russia, this mechanism may include the following components:

- (1) direct budget financing of innovative projects;
- (2) indirect support by means of major tax breaks for the first two years of production, with smaller breaks for the next two or three years;
- (3) eliminating the tax on profits.

Capital expenditure for subsequent expansion of production will be drawn from profits, stock offerings, credit, and investments.

Given Russia's technological base, we may expect that, with reasonable financial and technical policies, the country will be a leader in the production of clean and efficient Stirling engines operating on alternative fuels.